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SPECIAL REPORT

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## FURTHER MEASURES OF CHROMOSPHERIC SPICULES

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REPORT AUTHORS: Walter Orr Roberts,\* Martha B. Shapley,\*\*  
Virginia K. Brenton,\*\* and Zdenek Kopal\*\*\* High Altitude Observatory of Harvard University and University  
of Colorado, Boulder, Colorado, Contractor on Reference Contract.\*\* Department of Electrical Engineering, Massachusetts Institute  
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## ABSTRACT

Two films of prominence spicules have been subjected to analysis. The general features of spicules described in an earlier paper by one of the authors have been confirmed. The earlier film, taken in December 1943, showed an average ejection velocity for the spicules of 38 kms./sec.; the later, taken in February 1946, showed a nearly doubled velocity of 72 kms./sec. and a higher number of spicules per picture. Strong observational selection affects the velocity results. We cannot be certain that these same velocities apply to the typical small spicules which appear with the greatest frequency.

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## I. GENERAL CHARACTERISTICS OF SPICULES

Minute spike-like prominences appearing at the very edge of the sun's chromosphere possess characteristics of behavior which justify our classifying them as a group of phenomena of special interest. In an earlier paper <sup>1)</sup> one of us called attention to this new class of solar prominences which he designated by the name "spicules," following the suggestion of Dr. Harlow Shapley. Most spicules were very faint and small, but displayed great activity, extremely short lifetimes, and relatively uniform behavior.

Thus far we have observed the spicules with the Lyot-type coronagraph at Climax only in the hydrogen line H $\alpha$ . The spicules near the poles of the sun have exhibited the closest conformity of the typical model of a spicule. Near large active prominences of other kinds spicules seem either absent or much more complicated in behavior. Possibly this is simply a latitude effect: typical spicules generally cluster near the poles, ordinary active prominences are far more abundant in lower latitudes. However, there is no sharp line of demarkation between spicules and small short-lived prominences of other sorts, nor is the clustering of spicules towards the poles at all striking. It is true that prominences, in general, move mostly toward the solar surface or tangentially to it. Spicules, on the other hand, generally exhibit radially outward movements.

To photograph spicules is difficult because of their small size and their faintness. They are much easier visual objects in the coronagraph, but because of the eye-strain associated with prolonged visual observations we have not succeeded well in studying them quantitatively by visual methods. However, this field should not be completely neglected. A coronagraph is probably necessary for successful spicule studies. Excellent seeing and low sky and instrumental background intensity are prerequisites.

From time to time we have taken films at Climax specifically for the observation of spicules. All films have been obtained with the birefringent filter made by Dr. John W. Evans, designed for a transmission half-width of about  $\frac{1}{2}$  A.

This paper summarizes some new measures made on the film of 12 December 1943 which was used in the earlier paper, <sup>1)</sup> as well as some measures on a new film obtained on 21 February 1946. Both films were exposed for about two seconds per frame on special 35 mm. Eastman Kodak film of type 103-H $\alpha$ . The earlier film contained 236 pictures taken at a rate of one picture per minute; the later film has 365 pictures taken at three pictures per minute. Both films were taken under conditions of excellent seeing and atmospheric transparency.

The general characteristics of spicules described earlier have been confirmed. In addition, we have subjected selected spicules to detailed velocity analysis. Some new statistics of spicule frequency and directional behavior have also appeared from our present analysis.

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<sup>1)</sup> W. O. Roberts, Ap. J. 101, 136, 1945.

## II. RESULTS FROM FILM OF 12 DECEMBER 1943.

Miss Brenton's analysis of the film of 12 December 1943 involved the identification of 361 spicules which possessed a mean lifetime of about 3.8 minutes. We define "lifetime" as simply the length of time during which we can identify a given spicule on the frames of our films. A spicule seen on one frame only on a one-frame-per-minute film is regarded as having a one minute lifetime. For films taken at this rate of lifetime in minutes is equal to the frame count between the frame of first appearance and the frame on which it is clear that the spicule has finally vanished. For short-lived spicules this count is extremely difficult to establish and has a large probable error compared with the lifetime of the spicule involved. Figure 1 displays the results of Miss Brenton's measures of the number of spicules possessing given lifetimes. As we go to shorter lifetimes the number of spicules observed increases very rapidly. Thus we substantiate the suggestion in the earlier paper that the drop in frequency given there for shorter lifetimes was probably the result of observational selection. We have also used a larger sample and more painstaking observations in the present study. Also, we have confirmed the earlier suggestion that the double maximum on the frequency histogram of the earlier paper was not significant. Figure 1 not only shows the very great relative frequency of the very short-lived spicules, but also suggests that many more spicules may appear below the level of sensible detection on the films thus far analyzed. Near the lower lifetime limit the statistics are somewhat unreliable. In particular, the frames showing a spicule a single time might well be simply frames of somewhat better seeing and more precise occultation surrounded by frames of poor or ordinary seeing: on such good frames a somewhat longer-lived spicule of very small size might have been visible, even though on following and preceding frames it was not, because of the poorer seeing and occultation. By the time another frame of good seeing came along the spicule might actually have faded out. In such a case a lifetime of one minute might be assigned to it instead of a proper figure of three or four minutes. Also, a number of truly short-lived spicules might go totally undiscovered on the frames of poorer seeing. The only solution of such problems is to take many more pictures per minute.

A measure of the importance of the effects of uneven seeing and occultation is given by the fact that on the frames on which new spicules were discovered, presumably frames of better than average seeing, an average of 2.6 spicules was found. If the seeing and occulting were uniform so that the discovery probability remained equal on all frames and if the spicules were distributed at random with time, as seems probable, one would have expected to find only 1.5 spicules per frame. (Total number of spicules divided by total number of frames in film.) Another way of expressing the same fact is to point out that there were 99 frames out of the 236 on which no spicules were identified for the first time.

The length of the arc of the sun's limb included in these spicule-frequency determinations was about  $85^{\circ}$ , so that one could expect, on this film, to discover 0.02 new spicules per degree of arc per minute of time.

HISTOGRAM SHOWING THE FREQUENCY DISTRIBUTION OF THE  
LIFETIMES OF SPICULES

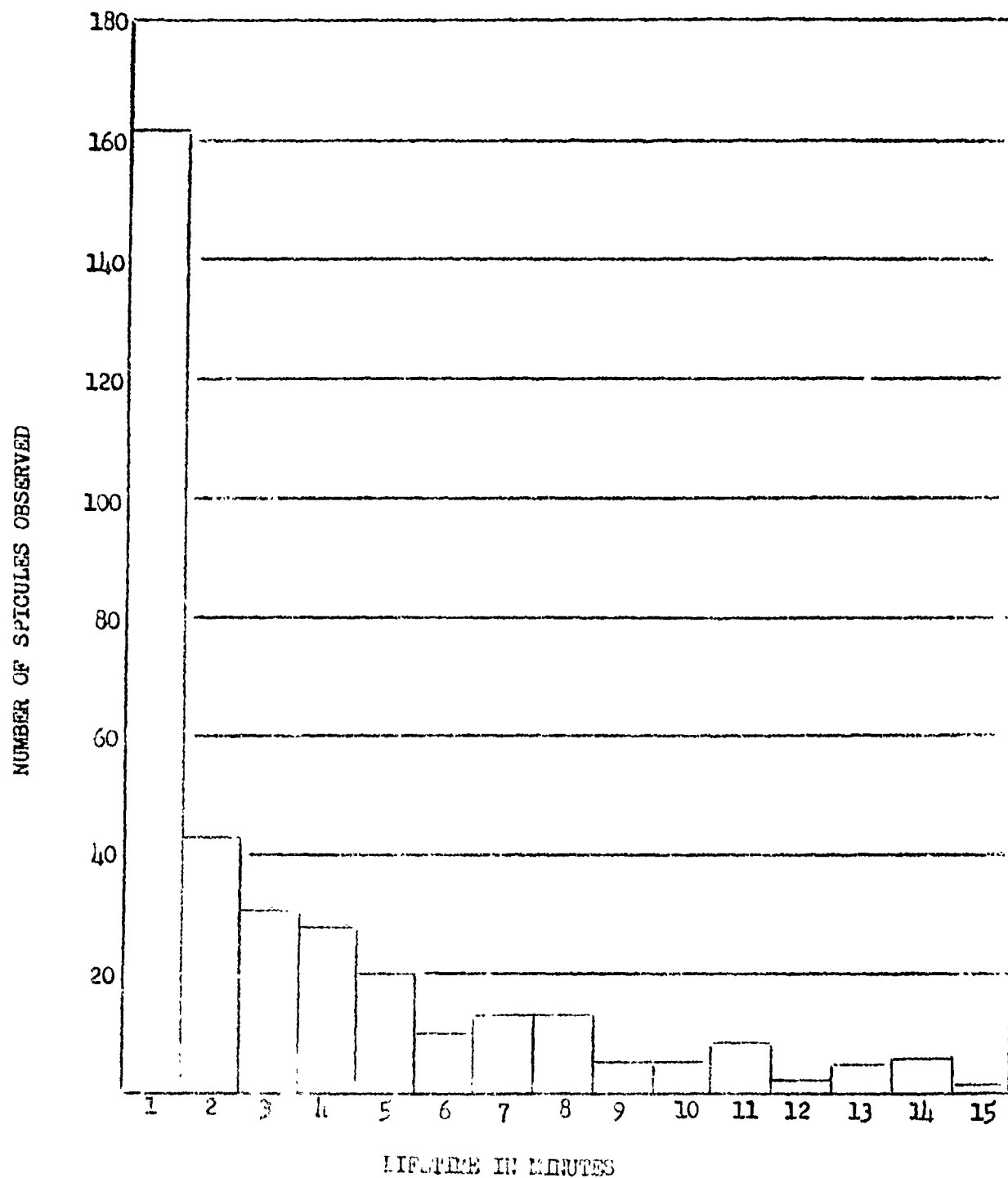


FIGURE 1

The average lifetime for the spicules of this film was 3.3 minutes, excluding spicules of lifetimes greater than 15 minutes, which it is perhaps legitimate to do in view of the less clearly typical behavior of these longer-lived spicules. Including all spicules the average lifetime is still less than four minutes.

Approximately 80% of all spicules were elongated in a direction classed as radial, rather than oblique or tangential. The mean lifetimes of the remaining prominences which were not radial was about seven minutes, or substantially longer than for the more frequent radially elongated spicules.

Twenty-three of the spicules were chosen for velocity analysis. These 23 objects were selected because their images were large enough on a sufficient number of frames to allow measures of some reliability. They were not, however, typical spicules. Their mean height was about 15,000 kms. which makes them substantially larger than an average spicule. Only about one-fifth of them were classed as radial. Furthermore, their mean lifetime was about 16 minutes, or almost five times as long-lived as an average spicule. For the smaller spicules velocity determinations are far more difficult.

The mean velocity of ascent for these features was about 38 kms. per second. This figure compares with about 30 kms./sec. which one of us very roughly estimated in the earlier paper to characterize a typical spicule.

### III. RESULTS FROM FILM OF 21 FEBRUARY 1946

The second film analyzed had been taken at the more suitable rate of three pictures per minute, which made possible an improvement in the frequency statistics for the short-lived spicules. All analysis of this film was carried out by Mrs. Shapley. This film confirmed the general behavior of the spicules observed on the 1943 film. The majority of spicules were less than 4000 kms. in height at maximum. As in the earlier film, the typical spicule grows upward at a relatively rapid rate, then seems merely to disappear with no obvious motion. The lower portions may return to the chromosphere or they may simply fade out; it is difficult to differentiate between these possibilities on the basis of appearance, though appearance favors the fading-out process.

The first 50 frames of this film were analyzed in detail. On the average 11 spicules were visible on a given frame. This is approximately twice the number of spicules per frame seen on the earlier film. Even casual inspection of the film shows the higher apparent spicule activity on this film as compared with the earlier film. Mean lifetimes of the spicules were not explicitly derived. One can estimate very roughly from the data list that about five minute lifetimes were found for a large number of the spicules. However, as the data were treated, the spicules were tabulated on each frame and at each position angle without regard to the previous appearance on preceding frames, so that explicit deduction of the

average lifetime is impossible without further examination of the original film.

Table I shows the frequency with which the apparent heights of prominences fall within the given class intervals. Here again the height is not the maximum height of the spicule, but the height of all spicules observed on all frames without regard to their appearance in preceding or following frames. Thus, a spicule showing as a tiny spot at the limb would be classed in its discovery frame as a small spicule, even though in a later state of development it would be listed in the higher classes. The number of times a spicule is counted in this table is thus proportional to its lifetime.

TABLE 1

Height kms.	0 to 1840	1840 to 3690	3690 to 5530	5530 to 7380	7380 to 9220	9220 to 11,070	11,070 to 14,760	over 14,760
Number	93	296	101	61	42	22	26	27

Ten spicules were subjected to special study. The mean lifetime of the objects chosen for study was 9.3 minutes. All of the ten were notably conspicuous spicules. The average height of these ten features was about 15,000 kms., or about four times the height of a typical spicule.

The average velocity of ascent for these ten conspicuous spicules was about 72 kms./sec., or approximately double the velocity average from the earlier film. If this doubling of velocity of ejection of the large features is also shared by the smaller and more frequent spicules, as it seems not unreasonable to suppose, then the result is of great importance. If further studies show the average velocity and frequency of the spicules to be correlated with other indices of solar activity cycle, as these two films might lead one to speculate, the result will be of still greater interest.

One feature of the analysis which appears noteworthy is the absence of a clear-cut relation between the velocity of ascent of the spicules and the maximum height which they attain. The selected spicules studied on the later film did not reach greater heights, on the average, than those of the earlier film in spite of their substantially greater velocities.

#### IV. FURTHER WORK NEEDED

The supply of good spicule films from the Climax coronagraph between 1943 and 1949 is very limited. Two or three others are available and must be studied, and more spicule films will be taken at Climax. A substantial number of good spicule films for 1949 is available and these will be analyzed also. They appear to show still greater activity than the 1946 film.

The Lamm Instrument measuring microscopes used for the prominence analysis are excellently suited for accurate positional measurements, but are not ideal for prominence studies because the observer cannot trace directly on paper the objects he sees, nor can he advance the pictures into accurate register from frame to frame in any simple automatic manner or at speeds anything like motion picture projection speeds. These factors impose limitations upon the speed and diversity of the analysis that can be done on the machines.

A further effort must also be made to study the typical spicules on both of these films, even though these are much harder to analyze than the more conspicuous objects which form the basis of the studies we have reported here. We would like also to obtain measurements of typical spicules of both films, using identical procedures and identical observers, in order that effects of personal selection or other personal equation factors can be minimized. The main limitation upon further beneficial analysis of the 1943 film is its slow picture rate of one frame per minute. This limits sharply the usefulness of the film for further study of spicule frequency or velocity.

We must also endeavor to evaluate quantitatively the importance of the observational selection which arises out of the fact that the number of spicules visible per picture varies sharply with the seeing and with the accuracy of the occultation at the instant of exposure.

Particularly important, after we obtain velocities for a large number of ordinary spicules will be the determination for both films of the frequency of spicules per unit time per unit arc of the limb, much as has been done for the earlier film by Miss Brenton. The specific identification and typing of the spicules as done in the first film should also be extended to the second. In the study of the second film, Mrs. Shapley carried out some frame-by-frame sketching of certain spicules. The results of this work have not been reported here, but will be submitted separately. Similar attempts to trace typical spicules much as Mrs. Shapley has done for the larger ones should also be attempted on other spicules of both films.

Continued pursuit of these spicule measurements is made increasingly important by current developments in chromospheric and coronal theory, such as the paper by Schwarzschild,<sup>2)</sup> some of the papers by Biermann, Alfvén or the two papers by E. H. Thomas.<sup>3)</sup> In Thomas' paper superthermic jets of gases passing through the chromosphere

2) Ap. J., 107, 1, 1943

3) Ap. J., 108, 130, 1943 and Ap. J., 108, 142, 1946

are considered as a mechanism for supplying the energy of the chromosphere and the corona, and as the source of the high kinetic temperatures assumed to characterize these regions.

Some reference has been made to observations of other small surge-like or spike-like prominences by other observers. In some cases, and in particular in the observations of Bugoslavskaya,<sup>4)</sup> we feel that the particular prominences analyzed are somewhat different features from the small faint objects we have intended to denote by the term spicule.

Both the spicules and all larger prominences probably contribute substantially to the supply of energy sustaining the corona and prominences. The overwhelming predominance of apparent outflow displayed by the spicules makes them especially useful in the theories for the mechanical transport of energy through the photosphere which are now being developed by many theoretical workers. We therefore hope to publish additional reductions of our films of these phenomena in the near future.

In conclusion, we wish to express our thanks to the Office of Naval Research which has financed the research work described here, and to the Bureau of Ordnance of the Navy Department which has made available to the Office of Naval Research the Mann Instruments and observers, and the other facilities of the Computation Laboratory at the Massachusetts Institute directed by Dr. Kopal. The measurements were carried out as a part of a study of the development of improved apparatus for reduction of prominence films.

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*Walter Orr Roberts*

Walter Orr Roberts

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<sup>4)</sup> Astronomical Journal of the Soviet Union XXIII, 4, 1946.